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Clay creep and displacements: influence of pore fluid composition

Dario M. Pontolillo[a], Jacopo De Rosa[a], Gianvito Scaringi[a], Caterina Di Maio[a,*]

[a] *University of Basilicata, via dell'Ateneo Lucano 10, 85100 Potenza, Italy*

Abstract

Time dependent shear displacements in clay soils under constant effective stresses can also be induced by changes in pore fluid composition. This paper presents the results of laboratory tests carried out on a sodium bentonite and on samples of the *Varicoloured Clays* formation outcropping east of Potenza, Southern Italian Apennines. The soils reconstituted with a 1M NaCl solution were submitted to shear tests under constant shear stresses in two different conditions: i) after shearing to the residual state, and ii) intact at various OCR. The applied shear stresses were lower than the residual strength of the materials reconstituted with the salt solution (residual friction angle, $\varphi'_r \approx 15°$) and higher than that obtained with distilled water ($\varphi'_r \approx 5°$). While exposed to 1M NaCl solution, the specimens didn't experiment creep; on the contrary, exposure to distilled water made the displacement rate increase greatly. The decrease in pore ion concentration obliterated the over-consolidation effects.

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Keywords: clay; pore fluid composition; creep; strength; failure

1. Introduction

Creep is defined as the progressive, irrecoverable deformation of a soil element under a state of constant effective stresses [1]. An increase in the deviatoric stress level can result in a deformation response characterised by three successive phases which are named primary, secondary and tertiary creep, characterised by decreasing, constant and increasing strain rate respectively. The actual strain pattern is hypothesised to depend on the type of soil, stress level and stress history [2-5].

* Corresponding author. Tel.: +39 320 4238545.
E-mail address: caterina.dimaio@unibas.it

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Deformations at molecular, particle and aggregate levels can contribute to the creep phenomenon [6]. The different levels of deformation can be ascribed to two groups of micro-processes: rearrangement of matter and rearrangement of particles or aggregates [7]. Failure of cemented bonds or increase in the ratio of tangential to normal forces at the interparticle contacts are among the processes which can lead to creep rupture for loss of strength [1,7,8,9]. Loss of strength can be also caused by chemical variations of the pore fluid (among others: [10]). It was shown that such a type of deterioration can cause shear displacement with a typical creep pattern in soil specimens subjected to constant Terzaghi's effective stresses. Some results [11] refer to a sodium bentonite reconstituted with distilled water and with NaCl solutions at various concentrations. An analogous experimentation was also carried out on the *Costa della Gaveta* soil [10,12]. With the aim of analyzing the viscous behavior of the soils on pre-existing discontinuities such as slip surfaces, the specimens were first sheared under constant displacement rate until the residual conditions and then submitted to creep tests, under constant normal and shear stresses and in the absence of chemical gradients. At equilibrium, the specimens were exposed to water, inducing ion diffusion from the pores to the cell water. This caused shear displacement acceleration with a pattern very similar to that of tertiary creep [4]. In order to extend the experimentation to intact materials, this paper analyses the behavior of bentonite specimens reconstituted with 1 M NaCl solution, consolidated to different normal stresses, unloaded to different OCR values, and then submitted to shear tests under controlled shear forces, initially without chemical gradients and then with exposure to distilled water.

2. Materials

The tests were performed on the *Costa della Gaveta* soil and on a sodium bentonite. The first soil is characterised by high values of the clay fraction (*c.f.* > 40%) which is constituted by illite-muscovite, kaolinite and smectite [13]. The bentonite, provided by Laviosa Minerals SpA, Livorno, Italy, with *c.f.* ≈ 80%, is mainly composed of Na-montmorillonite. Some properties of the soil samples used for this experimentation are reported in Table 1.

Table 1. Physical characteristics, Atterberg limits and index properties of the tested soils.

Material	Borehole-Sample	Depth (m)	c.f. (%)	γ_s (g/cm^3)	w_L (%)	w_P (%)	I_P (%)	A	w_L(%)
					distilled water				*1 M NaCl*
Costa della Gaveta soil	S7-CD2	28.0 - 29.6	52	2.67	65.2	26.2	39.2	0.75	64
	I9c-CD18	4.00 - 4.35	33	2.67	77.8	28.6	49.2	1.49	
	S10-CD20	9.3 – 9.5	47	-	65.4	-	-	0.52	
	I15-CD6	18.3	60	2.65	123	46.9	76.1	1.27	68
Bentonite	-	-	82	2.75	324	44.8	279.2	3.4	116

3. Methods and results

The shear tests were carried out by means of different devices: the Casagrande and the reversal direct shear, the Bishop and the Bromhead ring shear. The devices were used both in the conventional mode, at constant displacement rate, and under controlled driving shear stresses thanks to an *ad hoc* modification. The constant rate tests were carried out at v = 0.018 mm/min in the Bromhead apparatus and at v = 0.005 mm/min in the other devices. The specimens were generally reconstituted with NaCl solutions at different concentrations and with distilled water at the corresponding liquid limit (Table 1). The residual strength is independent of initial conditions, thus, the specimens used only for the determination of it, were also prepared with solution content lower than the liquid limit.

3.1. Shear tests at constant displacement rate

A number of shear tests was carried out on a sodium bentonite and on the *Costa della Gaveta* soil reconstituted with NaCl solutions at several different concentrations and submerged in the same solution, i.e. in the absence of chemical gradients [10,11,12,14]. The results were interpreted in terms of residual friction angle φ'_r, the residual cohesion intercept c' being null for both materials. The strength parameter has been found to vary greatly with the pore fluid composition, as shown by Figure1 that plots φ'_r against the molarity of the pore NaCl solution. Figure1b also shows the range of natural variation of Na^+ in the *Costa della Gaveta* landslide, highlighting that it is the range of the highest φ'_r gradients.

3.2. Shear tests under constant driving shear stresses

The shear devices where modified, as described in [10], in order to perform controlled shear stress tests on both pre-sheared specimens and intact specimens. Several tests were performed on specimens pre-sheared to the residual condition in order: *i)* to have a deeper insight in the viscous behaviour of active landslides moving along a slip surface in the residual condition, and ii) to investigate the soil behaviour in an ideal "steady state" condition, in which the soil slips continuously, with constant volume and structure and under constant average normal and tangential interparticle forces [11].

The stress conditions of some specimens reconstituted with, and immersed in, a 1 M NaCl solution are shown by Figure 2 in which the applied stresses are compared to the residual strength of the materials in the solution and in water. It can be seen that the values of τ applied to the three bentonite specimens C1-C3 are intermediate between the values of residual shear strength in 1 M NaCl solution and in distilled water. Similar test conditions were applied to the *Costa della Gaveta* soil.

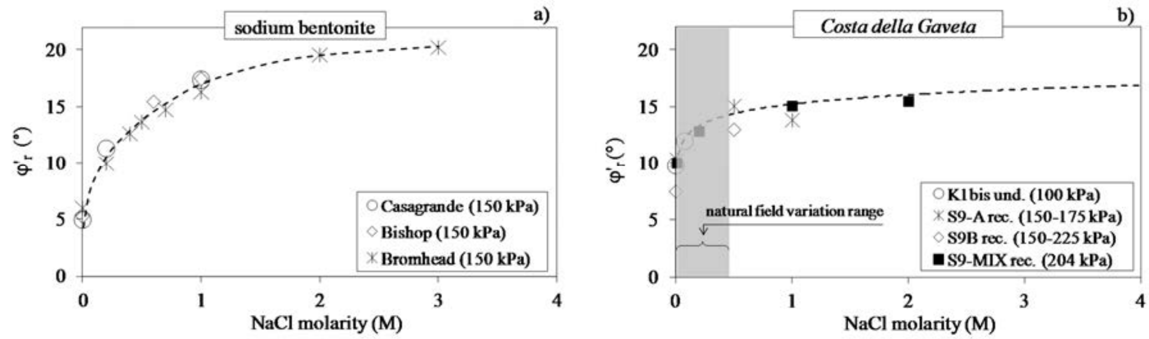

Fig.1. Residual friction angle φ'r against the pore NaCl solution molarity for: a) a sodium bentonite [11], and b) Costa della Gaveta soil with indication of the range of the field natural variation [12].

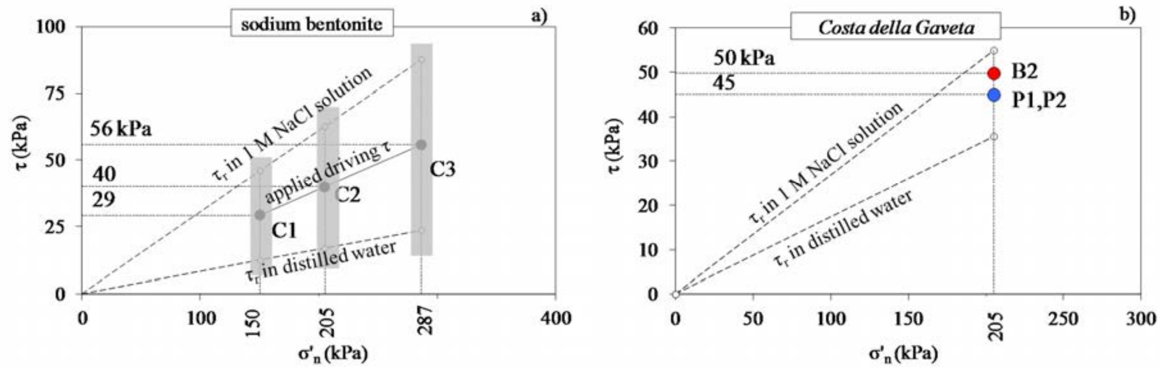

Fig. 2. Stresses applied during the creep tests to pre-sheared: a) bentonite specimens [11], and b) Costa della Gaveta soil, and residual shear strength lines of the materials in water and in 1 M NaCl solution [10].

Under the considered driving shear stresses, all the specimens underwent small shear displacements, with rates *v* decreasing over time to negligible values, i.e. $v < 10^{-6}$ mm/min, or even to a complete stop (Fig. 3). This behaviour was expected on the basis of previous studies [e.g. 6,15] which show that the residual shear strength (that for the considered soils in the considered conditions is the strength evaluated with a 1 M NaCl pore solution) can be considered a creep threshold. However, the residual strength can decrease, lowering the threshold, as shown by the subsequent experimentation during which the cell fluid of the specimens, with the only exception of P2, was replaced by distilled water, thus imposing concentration gradient. This, in turn, caused ion diffusion from the pores to the cell water which was renewed daily, to remove the diffusing ions, and analysed. The specimen P2, submerged in 1 M NaCl solution all the time, did not exhibit any further displacement. All the other specimens, after exposure to distilled water, underwent horizontal displacements with rate increasing up to $v = 10^{-2}$ mm/min (Fig. 3) in correspondence to the maximum displacement allowed by the devices.

In order to evaluate the available strength at "failure", soon after the stop, the shear devices were re-converted to the controlled-displacement mode and the specimens were sheared further while exposed to water. As expected, the available shear strength was found to be equal to the applied shear stress [11]. The decrease in strength during exposure to distilled water can be interpreted with the relation - between pore solution concentration and residual friction angle - evaluated in drained conditions for specimens exposed to the same solution as the pore solution, i.e. in the absence of chemical gradients [11].

Pore fluid composition influences peak strength as well [16], tests similar to those just described for pre-sheared specimens were thus also carried out on intact reconstituted materials. Three specimens (I1, I2 and I3) were saturated with 1M NaCl solution, immersed in the same solution and consolidated to 205, 400 and 800 kPa respectively. At equilibrium, I2 and I3 were unloaded to 205 kPa. After swelling (about 4 days long) the specimens were submitted to a constant shear stress $\tau = 40$ kPa (Fig. 4). As expected, this stress caused negligible displacements with rates decreasing to zero. Once the displacement rate was practically null, the cell solution was replaced by distilled water, renewing it daily. As a consequence, and similarly to the pre-sheared ones, the intact specimens underwent displacements with increasing rates (Fig. 4a, b).

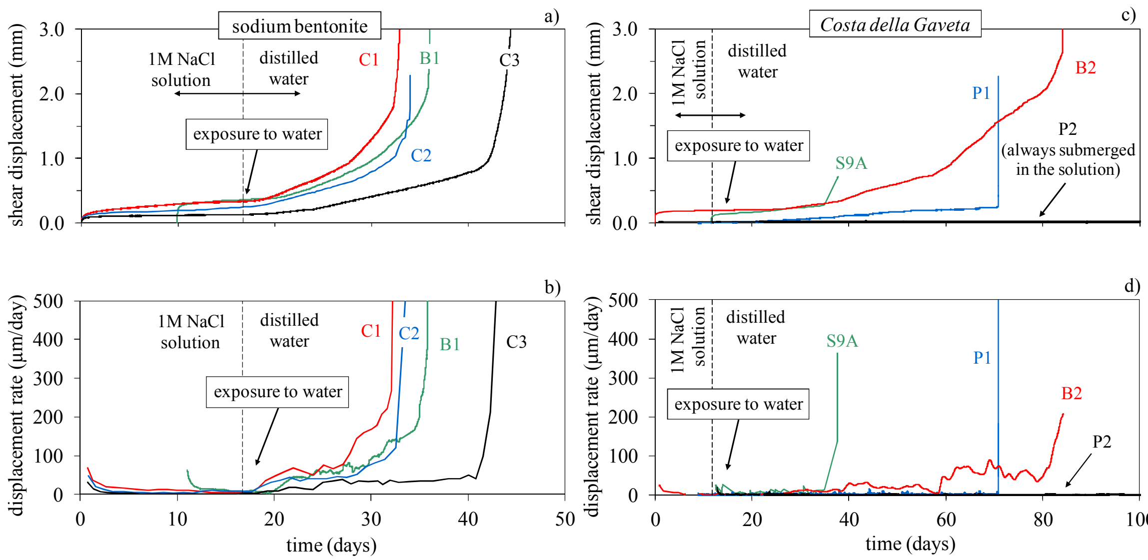

Fig. 3. Pre-sheared materials: shear displacement and shear displacement rate against time of bentonite (a, b) [11] and Costa della Gaveta soil (c, d) [10] reconstituted with 1 M NaCl solution and sheared under stress-controlled conditions.

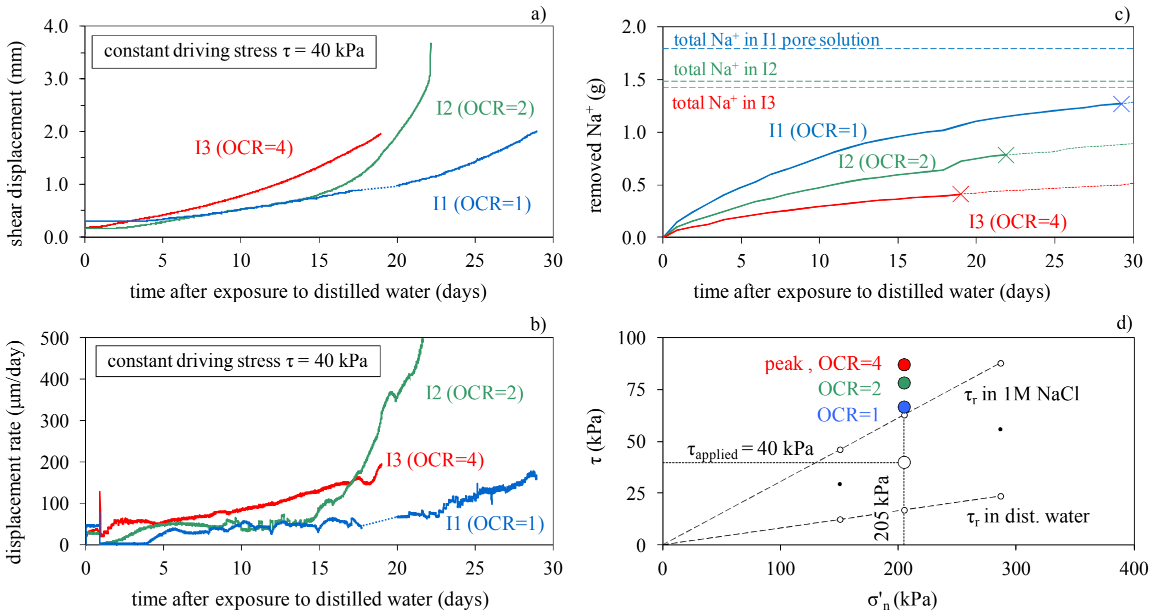

Fig. 4. Intact bentonite: shear displacement caused by exposure to water (a); shear displacement rate (b); Na+ removed from the pore solution compared to the final expected values (c); peak and residual strength in distilled water and in 1M NaCl solution and applied shear stress (d).

The used devices allow only very small shear displacements. To overcome this experimental limit, which doesn't permit a clear understanding of the dependence of the displacement rate on OCR, further modifications to the Bishop ring shear apparatus are currently being carried out and the processes will be investigated further. In the meanwhile, other aspects of the material behavior can be observed and analyzed, such as those shown in Figure 5. Soon after the stop imposed by the devices, the specimens Ci were submitted to a further shearing phase under constant displacement rate. The cell water continued to be renewed in order to remove the ions which were diffusing from the pores. Figure 5 plots shear strength against shear displacements evaluated in this phase, showing that, notwithstanding the differences in the original peak shear strength due to the three different OCR values, the specimens exhibited almost the same strength and similar strength trend over time. This behavior suggests that exposure to distilled water of the material reconstituted with the salt solution had been sufficient to cancel the previous stress-strain history of different over-consolidation.

4. Conclusion

A reduction in pore solution concentration makes the shear strength of clay soils decrease. Under constant effective stresses, the mechanical deterioration caused by such chemical variation can cause deformations and shear displacements with rates that can increase until values typical of failure.

In the case of the behaviour along a pre-existing slip surface, the decrease in strength during exposure to distilled water can be interpreted with the same relation between pore solution concentration and residual friction angle as that evaluated for specimens exposed to the same solution as the pore solution, i.e. in the absence of chemical gradients. For intact materials, the process can be more complex and further experimentation is required for a deeper understanding. First results seem to show that exposure to distilled water can cause shear deformation of intact over-consolidated soils and, in the same time, the obliteration of the previous over-consolidation effects of the stress-strain history.

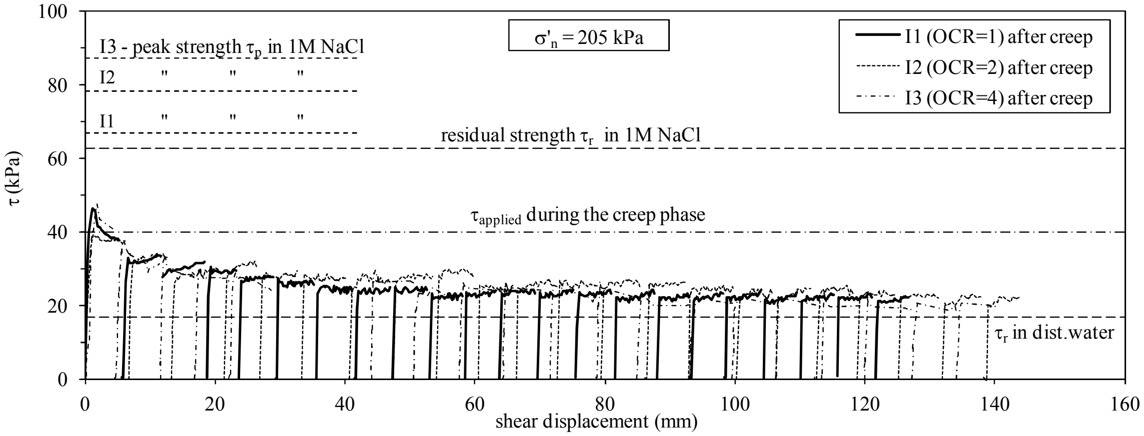

Fig. 5. Shear strength against shear displacements of the bentonite specimens after the creep "failure" and comparison with the residual and the peak strength of the material reconstituted with 1 M NaCl.

Reductions in pore solution concentration have been verified to occur in many geological clay formations in different Earth's regions [11]. The results reported in this paper can thus find application in many practical problems, among which those of the evaluation of possible causes of slope deformation and landslide movements.

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